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Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning

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ABSTRACT

The UK Government is committed to ambitious targets to reduce carbon emissions. The large tidal ranges in estuaries on the west coast of the UK make the deployment of tidal barrages an attractive proposition, and repeated feasibility studies have been undertaken. No barrage scheme has yet been taken forward, and one factor contributing to this reluctance to proceed is the significant environmental impacts that could result from the barrage construction and operation. This paper provides a detailed review of the current understanding of the potential ecological and social impacts of tidal barrages, including a case study of La Rance in northern France, and a discussion of strategies for mitigating barrage impacts. The review considers how more comprehensive ecological modelling could reduce uncertainty in predicting the impacts in specific estuaries, and discusses the use of Multi-criteria Analysis and ecosystem valuation as tools for evaluating the disparate costs and benefits of barrages schemes.

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1. Introduction

In response to international, regional and national drivers on climate change and energy security, the UK Government has committed to ambitious fossil fuel reduction targets. The 2008 Climate Change Act set legally binding 'carbon budgets', to cut UK carbon emissions by 34% by 2020 and at least 80% by 2050 [1]. Electricity generation accounts for 27% of carbon emissions: it is predicted that meeting the emission reduction targets will require 30% of UK electricity to be generated from renewable sources by 2020, and that the sector will have to be almost entirely decarbonised by 2050 [2]. A diverse range of renewable electricity sources have been, and will continue to be, deployed as part of the UK energy strategy, and marine energy has the potential to play an important role.

The large quantity of electricity that could be generated by tidal barrages makes them a particularly attractive renewable energy option. One of the highest profile possibilities for the utilisation of tidal power is the Severn estuary in southwest England, which, alone, could provide 5% of the UK's electricity requirements [3]. In addition, the combined output of tidal barrages in four estuaries in northwest England could meet approximately half of the present energy needs of that entire region [4]. The longevity of tidal barrages is also a considerable advantage. A tidal barrage could last 120 years, compared to 40 years for a nuclear power plant and just 20 years for a wind farm [5].

The UK Government first investigated the possibility of a Severn tidal power scheme in 1925 [6], and multiple feasibility studies have been commissioned since. The most recent study concluded in 2010 that there was no convincing case for a barrage in the Severn in the immediate term [7], but a consortium of private developers has recently revived proposals for a barrage [8]. The Severn estuary is only one possible location for a tidal range power scheme in the UK. Assessments of tidal power from the Solway Firth have been undertaken since the 1960s [9], and similar reviews of possibilities for smaller estuaries including the Mersey, Conwy, Wyre and Loughor began in the 1980s [10].

As yet, however, no tidal barrages have been commissioned in the UK, in part because the environmental impacts of such schemes would potentially be significant. A continuous, obstructive tidal barrage could have negative effects on the ecosystem and society by modifying water circulation, sediment behaviour, water quality and habitats, restricting the passage of migratory fish, posing a collision risk to fish and marine mammals, and changing land and amenity uses [11]. The environmental impacts can be compounded because estuaries are often important conservation sites. The Severn, Mersey, Morecambe Bay, Dee and Solway Firth all contain protected areas, which include habitats and species protected under the international Ramsar Convention and the EU Habitats and Birds Directives [12].

This paper reviews the status of current knowledge about the potential ecological and social impacts of tidal barrages by drawing together what is known from existing tidal barrages around the world, the effects of other coastal infrastructure, and predictions about proposed UK schemes (much of which is in the grey literature). La Rance in northern France is used as case study to demonstrate specific changes that have been documented following barrage construction. Strategies for mitigating environmental impacts are discussed, including consideration of how the cost of alternative schemes compares to that of a conventional barrage design.

Barrages have only been deployed in a handful of estuaries worldwide, and proposed mitigation measures remain almost entirely untested, and so the paper also discusses how coupled hydrodynamic and ecological models could be used to reduce uncertainty about barrage impacts. Understanding likely impacts is essential in evaluating barrage schemes, but is only one part of the process. Barrages have both positive and negative effects, and the decision to accept or reject a barrage proposal requires a transparent method to assess social and ecological trade-offs. The paper concludes by considering the role of Multi-criteria Analysis and economic valuation of environmental change as tools for evaluating the costs and benefits of a tidal barrage and so supporting barrage planning decisions.

2. Potential ecological impacts

2.1. Construction and presence of a physical structure

2.1.1. Benthic communities

The construction of a tidal barrage will disturb seabed sediments. Plumes of sediment created during these processes may have detrimental consequences for benthic marine life through direct smothering as the suspended sediment is deposited [13] and by interference with feeding or digestion while high concentrations of sediment remain in suspension [14]. The degree of the impact will depend on the quantity of sediment disturbed, as well as on the existing seabed type and communities present [15]. The instantaneous deposition of large quantities of sediment, such as during the disposal of dredged material, can result in total mortality [16], while burial beneath thinner layers up to 25 mm thick may have no discernible effect [17]. If the deposited material is not identical to the sediments on which it settles, or has been contaminated, the rate of mortality may increase [17,18].

The community that immediately recolonises a disturbed area is likely to differ from that which existed prior to construction. Opportunistic species will tend to dominate, and introduced and invasive species may rapidly exploit the disturbed site [19]. It may take more than two years for a community to return to a closer resemblance of its original state [15].

Habitat will be lost beneath the footprint of the tidal barrage, but the surface of the new structure will provide new areas for colonisation. The presence of any hard substrate in areas of soft sediment (such as a muddy estuary) will act as a settlement surface, attracting species not otherwise able to colonise the area and so increasing biodiversity. Evidence suggests, however, that the assemblages of species colonising artificial structures differ from those on natural reefs [20]. The principal reasons for the differences are that artificial constructions have little similarity to natural habitats. Walls and pilings tend to be vertical, homogenous structures, which are made of unnatural substances, and lack microhabitats and areas of refuge [11]. They also create shelter and cause shading of the sea floor, extending the footprint of the impact.

2.1.2. Passage of mobile and migratory species

Tidal barrages that obstruct the entire width of an estuary would inhibit the movement of marine species. Barriers, such as dams, that prevent anadromous fish (for example lamprey and shad) from reaching their freshwater breeding grounds are a known factor in the decline and extinction of these species [21]. Dams and similar obstructions also have implications for marine fish and crustaceans which, while not migratory, nonetheless undertake significant movement up- and down-stream as part of their normal seasonal activity as they transit between breeding, nursery and feeding grounds [22].

Experience with hydroelectric power plants illustrates that it is possible for fish to pass through the turbines and sluices contained within a barrage. However, turbine passage brings significant risk of injury or mortality from sheer stress, pressure changes, cavitation and collision [23]. Fish also appear to be at greater risk of predation in the proximity of a dam, which may be a result of the concentrating effect of the structure, or of fish becoming stressed or disorientated following turbine passage [21].

2.1.3. Noise

Noise causes disturbance, stress and potentially physical injury to marine life, and its impact can extend several kilometres from the source [24,25]. High noise levels during the prolonged construction phase of tidal barrages are of particular concern [26]. Noise may affect many different marine animals, including mammals, seabirds and fish [26–29], although the former make only limited use of turbid estuaries such as the Severn [30]. Sound also plays an important role as an orientation cue for the pelagic larvae of invertebrates, whose ability to detect suitable settlement sites may be affected by anthropogenic noise [31,32].

Noise will also be generated during the operation of tidal barrages, although the potential effects are not well understood. It is known that marine mammals can detect the noise created by an operating wind farm [33], although the low levels are unlikely to result in physical damage to the animals [27]. As the turbines are located below the surface, barrages are likely to create more underwater noise than wind farms during operation. Maintenance will also result in intermittent periods of higher noise levels [26].

2.2. Changes in water level

Tidal barrages have a significant effect on sea levels within the impounded basin, usually reducing the tidal range by about half [34]. There are different types of barrage design which can produce electricity on ebb tide only, flood tide only, or on both ebb and flood tides (two-way generation). The most common mode of operation is ebb-generation: the incoming tide flows though sluices to fill the landward basin until the gates are closed at high water. The water is then released through the turbines once the level of the outgoing tide seaward of the barrage has fallen far enough to create the required head. This altered regime prevents the tide within the basin from receding to as low a level at low water as previously [4].

Attempts have been made to predict the specific changes to the water level under ebb-generation scenarios. A barrage in the Severn, for example, could increase the mean sea level in the basin by 3 m, and reduce the spring tidal range from 12.3 m to 4.5 m [35], while a barrage across the mouth of the Mersey estuary could increase the upstream low water level by 4 m and reduce the tidal range by up to 60% [11]. The effect of holding back the tide prior to ebb generation also results in an increased period of high water that continues for several hours [34], and may raise the level of the water table [36].

The effects on sea level extend to the open sea. The tidal range could be reduced by 10% in the area immediately downstream of a Severn barrage [34], and the barrage could continue to influence the tidal range as far as 100 km seaward [35]. Smaller estuaries are too short for resonance effects, so the far-field implications will be reduced [37]. Conversely, were tidal barrages to be deployed in multiple locations, modelling suggests that the effects on sea level could become more widespread. The construction of a series of barrages in the Severn, Dee, Mersey, Morecambe Bay and the Solway Firth would reduce the tidal amplitude at the barrage locations, but could potentially increase the tidal level on the coast of Ireland by up to 20 cm [11].

Uplifting the level of low water within a tidal barrage basin will permanently submerge a considerable area of what was previously intertidal habitat. A Severn barrage could reduce the upstream intertidal area by 76%, which, in the case of a barrage between Cardiff and Weston-super-Mare, would result in the loss of 14,428 ha intertidal habitat [38]. Other estimates place the loss of intertidal area at 20,000 ha [35].

The intertidal area is not a homogenous feature, and the exact ecological implications of any loss of habitat will depend on the specific biota found in the affected location. The intertidal areas of the Severn and other hypertidal estuaries on the west coast of Britain contain large expanses of mudflat and saltmarshes. Environmental scoping studies and impact assessments for tidal barrage developments focus particularly on the implications that the loss of these habitats would have for wading birds and waterfowl [39–41]. This reflects the emphasis of statutory instruments on the protection of the migratory bird populations supported by UK estuaries [12].

The survival of bird populations depends on the abundance of, and energy available from, prey, the size of the feeding area and the time available for feeding [42]. The availability of breeding and nesting grounds is similarly crucial, and species such as the Redshank (*Tringa totanus*) are particularly vulnerable, as about half of Britain's breeding population of the species nests in saltmarshes [43]. The loss of feeding and breeding grounds resulting from the changes in sea level associated with a tidal barrage would be very detrimental to the affected birds, as evidenced by schemes such as the Cardiff docklands redevelopment which inundated 200 ha of mudflats in Cardiff Bay to form a freshwater lake [44]. Many wading birds are faithful to a particular site and so may not find new wintering areas. Even those that do are unlikely to thrive in the new environment as they are at a competitive disadvantage compared to the resident birds [36]. As habitat is lost, the increased competition at remaining sites increases the mortality rate within the wider population of the affected species [45].

Waders and waterfowl are just one group of marine species that will be affected by the loss of intertidal habitat. The intertidal zone is very important for the benthic micro-algae that make up the microphytobenthos (MPB) because their abundance decreases subtidally as the increasing water depth restricts the penetration of light. In estuaries, MPB primary production rates can exceed those of the phytoplankton found in the overlying water column, to the extent that the MPB may be the major source of primary production in fine-sediment dominated hypertidal estuaries like the Severn [46]. They also have a role in biogeochemical cycling and sediment stabilisation. The peak concentration of MPB in the Severn is found between mid-tide and mean high water neaps. The loss of 76% of the intertidal area following construction of a Cardiff-Weston barrage could see a corresponding reduction of 77% in levels of MPB primary production [46].

Habitat loss may, to some extent, be compensated for by other changes to the estuarine environment resulting from barrage construction, as discussed in Sections 2.4 and 2.5 below.

2.3. Waves and currents

A tidal barrage will shelter the upstream area from swell waves [48], as well as creating other local shelter and reflection effects. Local wave action may increase significantly where incoming waves interact with the outflows at sluices and locks [35]. The high energy flows from sluices and turbine outlets will also lead to significant local scour in the areas that surround them [11], which may prevent marine life from becoming established [49]. Barrages will also affect the currents in the wider estuary, reducing the upstream flow speed [11]. A Cardiff-Weston barrage could reduce the maximum tidal current in upstream areas by 45% [50].

The energy within a tidal flow is proportional to the cube of the velocity, so even small changes in current speeds may have significant implications. The altered tidal dynamics upstream of a barrage could increase stratification and reduce flushing rates, increasing the eutrophication risk [11,48]. Disruption of water flow also affects larval dispersal and the connectivity of communities [19], and this may influence ongoing recruitment of organisms and the re-establishment of communities following barrage construction.

2.4. Sediment dynamics

The energy of tidal currents is an important factor in determining the sediment dynamics within a marine system. This is of particular significance to estuaries such as the Severn, which are

characterized by high levels of suspended sediment [51]. The reduced current flows upstream of tidal barrages are likely to cause an overall increase in seabed deposition rates as fine sediments settle out of the water column [46]. There will, however, be local areas of increased current speed, in which sediment resuspension rates will also be increased [48]. The influence of a barrage on sedimentation patterns would also extend into seaward areas of the estuary [47]. The new sediment regime will not establish instantaneously, however, and there will be a period of enhanced sediment transport for months or even years after barrage construction [11].

The altered tidal regimes created by barrages, and the changes in the sedimentation pattern they induce, are expected to affect benthic communities within the estuary. In the Severn, which has been most widely studied in terms of the potential effects of tidal barrages, the predicted post-barrage scenario would suggest an increase in the abundance of *Cerastoderma edule* (cockles) and *Mya arenaria* (clams), as well as small burrowing crustaceans (such as the mud shrimp *Corophium volutator*) and sedentary annelid worms [47]. Conversely, the populations of species such as *Hydrobia ulvae*, *Macoma balthica* and *Nephtys hombergii*, which are associated with dynamic regimes, are likely to decline. Overall, the benthic species richness, abundance and biomass is expected to increase [47]. Microphytobenthos are found in greater densities on fine sediments, and so their distribution and abundance would also be altered [46].

Specific biogenic habitats of conservation importance such as *Sabelleria* (tube worm) reefs and *Zostera* (seagrass) beds may also be affected if sediment dynamics are altered [30]. The effect of the raised water level and increased length of high water stand may expose intertidal areas to increasing wind-driven wave erosion, with implications for remaining areas of mudflat and saltmarsh [52].

2.5. Water quality and pollution

Barrages are expected to reduce tidal flushing rates. A 40% reduction in flow rate could decrease the volume of water exchanged during a tidal cycle by 60% [37]. One potential implication of this is a decrease in upstream salinity [48], although the likelihood of this occurring is contested [51]. Changes in salinity would affect the extent to which marine species are able to penetrate the estuary, with implications for their local abundance [22]. Littoral vegetation may also be affected, with reed beds replacing saltmarshes if the influence of freshwater extends further down the estuary [52]. It is also possible that there may be minor changes to upstream temperatures and pH levels [53].

Reduced tidal flushing has implications for the dispersal of nutrients and contaminants. Dissolved oxygen levels are expected to rise following the construction of a barrage in the Severn [54] but an increased concentration of dissolved nutrients such as nitrogen may also be observed [53]. A rise in nutrient concentrations and decrease in suspended sediment could lead to a greater risk of eutrophication [55]. Discharged wastes could also build up landward of the barrage [56], perhaps resulting in failure of environmental quality standards near outfalls [53].

Tidal power plants may directly introduce pollution into the system, from antifouling coatings or as a result of chemical leakage from either components such as the gearbox or from fuel or oil discharges from maintenance vessels [28]. Increased pollution is also possible if contaminated material is reintroduced into the water column where sediment resuspension is increased during construction or as a result of increased local currents [11]. In the longer term, and across the wider estuary, the reduced tidal currents and reduced mixing that result will generally decrease resuspension of sediment and reduce the supply of contaminants [37]. The reduced water turbidity may also reduce the concentration of pathogens in the water column, as increased light penetration will increase the rates of photodegradation [53].

The clearer water may also improve conditions for suspension feeders [47], by supporting an increase in phytoplankton biomass and primary production [46]. This will in turn increase the food supply for the benthos and so enhance the carrying capacity of intertidal areas for feeding shorebirds [47], although any increase in food supply may not sufficiently compensate for the loss of intertidal habitat [6]. Changes in animal assemblages will also alter, for example, grazing patterns [46] and so the process of attempting to accurately predict ecosystem outcomes following the construction of a tidal barrage becomes very complex.

3. Impacts on society

Changes brought about following the construction of a tidal barrage will also impact on society. The physical presence of a barrage will affect other activities occurring in the area, which may include military exercises, or other renewable energy opportunities. Marine aggregate extraction may also be affected, by changes to both substrate composition and tidal regime, as this may alter the timing of access periods [56]. The suitability of dredge material disposal sites may also change, while telecoms cables, pipelines and outfalls may be affected by scouring, erosion or deposition [56].

Restriction of the ability of commercial and recreational vessels to navigate in the area due to obstruction, collision risk and reduced water depth could be a major implication of tidal barrages [35,41,57]. Conditions for small craft upstream of a barrage could potentially be improved, however, as a result of the longer high water stand [4] and the reduction in current speeds [56].

Fish populations, and hence the fisheries for them, may also be negatively affected by tidal barrages, although the balance of the environmental impacts on fish species important to commercial and recreational fishers is not known with any certainty. For example, the wider changes to sedimentation patterns in the Severn may ultimately increase the potential for commercial fisheries, as soft sediments could replace bedrock substrates seaward of the barrage [47]. Similarly, shellfish may be smothered by altered sediment regimes [57], or conditions for them within barrage basins may improve if reductions in water turbidity are not negated by the water quality issues associated with reduced flushing [56].

People will be disturbed by noise during both construction and operation. The seascape will be altered first during construction, and then for the longer term by the presence of the barrage [58]. In addition to the presence of the structure itself, a tidal barrage will influence the wider seascape by reducing the intertidal area and associated habitats such as saltmarshes, changing the morphology and substrate on beaches, and increasing water clarity [56,58].

The coastal environment contains shipwrecks and other pieces of archaeological and geological heritage, which may be damaged, disturbed or destroyed as a result of the direct effects of tidal power installations and the cables associated with them [57,59,60]. The indirect effects through alteration of hydrodynamics, shoreline morphology, water quality, tides, water level, and sedimentation regimes may also be detrimental to underwater heritage [59].

Recreation and tourism are important activities within the coastal zone, and any negative effects on wildlife as a result of tidal barrages may have economic and social implications for nature tourism such as bird and mammal watching and for leisure activities [56,57]. Tidal bores are also significant tourist attractions, especially that on the Severn, and would be lost following the construction of a tidal barrage [58]. Upstream of a barrage, bathing may become safer as result of reduced currents, but the changes to the tidal regime may

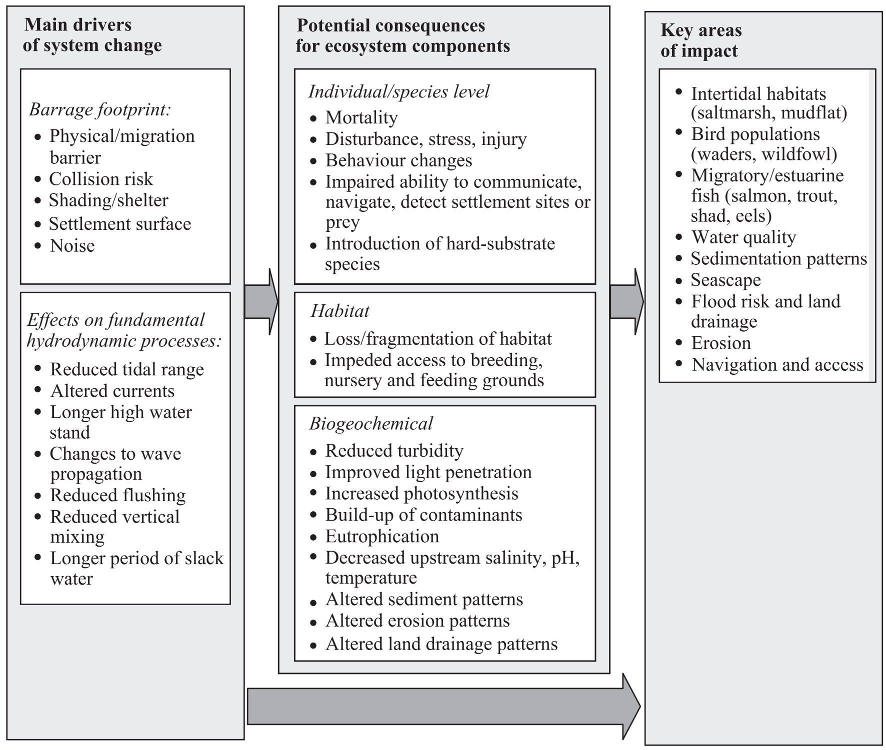

Fig. 1. A summary of the significant environmental impacts likely to arise from barrage construction.

also affect bathing water quality [56]. The tidal power plant itself may become a tourist attraction, as is the case for other large infrastructure projects. The Thames Barrier attracts about 200,000 visitors annually [10] and 350,000 people visit La Rance tidal barrage each year [54].

Tidal barrages could also bring ancillary benefits to society including road or rail links across the barrage and increased employment [4]. A barrage could also provide flood defences, which could protect against both tidal and river flood risks [11]. Conversely, flood risks could be increased as a result of saltmarsh erosion, the restriction of river outfalls by the longer high water stand, and the possible siltation of outfalls as a result of hydrodynamic changes [56]. Flood risk, freshwater supplies and local land use patterns may also be affected by changes to the water table and groundwater flow [61].

4. Case study of La Rance tidal barrage

Tidal barrages have the potential the impact significantly on the environment, with associated social implications (Fig. 1). Case studies can further improve understanding by providing information on the actual environmental consequences that have occurred in practice.

Globally, there are five tidal barrages that are, or have been, used to produce significant amounts of tidal energy: Annapolis Royal in Canada; Kislaya in Russia; Siwha Lake in South Korea; Jiangxia in China; and La Rance in northern France, which began operating in 1966. This latter barrage is most appropriate for a case study, as it is located closest to the UK and so is most similar in terms of the species within the ecosystem. There is also a relatively large amount of literature available about La Rance compared to other barrages. However, the assessments that have been undertaken do not provide comprehensive evaluation of all the generic impacts described above. This case study therefore focuses on how the tidal range and hydrodynamics of the estuary have changed, and the effects on benthic invertebrates and fish.

La Rance barrage has increased mean low water height in the basin by 2.5 m and decreased the tidal range by 40% [54]. Strong local currents are generated at sluice and turbine outfalls [62], but, in general, tidal current strength has reduced and the duration of slack water has increased from 15 min to 2 h under certain operating modes [54]. The volume of water exchanged with the sea has decreased by 30%, and the weakened ebb tides do not evacuate the suspended sediment brought into the basin on the rising tide [54].

The area occupied by the intertidal zone was reduced from 70% to 50% of the total surface of the basin following barrage construction [62]. Modifications to the sediment regime include erosion of the banks, relocation of sandbanks and an increase in fine sediments in caves and bays [62]. Turbidity levels have fallen to 5% of pre-barrage concentrations [54]. La Rance also has higher primary productivity than comparable estuaries [34]. Plankton blooms have been observed, but these are similar to those occurring in other local estuaries, so are not considered an effect of the barrage [55].

A review of the ecology at La Rance [54] suggests that marine life can adapt successfully to the presence of tidal barrages. The variety of subtidal habitats has increased since barrage construction, with a corresponding increase in species diversity and abundance. The increase in fine sediments in both subtidal and intertidal areas has stabilised previously sandy areas, and attracted more benthic organisms. The review [54] also hypothesises that the increased foreshore carrying capacity that has resulted has at least compensated, if not more than compensated, for the loss of intertidal area, and describes La Rance estuary as a more important site for waterbirds than the neighbouring Baie du Mont St Michel tidal flats [54]. La Rance was designated a Natura 2000 Site of Community Importance in 2004, in part due to the presence of 12 named bird species, nine of which are protected under the EU Birds Directive [63].

Within the intertidal area, the vertical range of algae has been reduced from 13 m to about 5–6 m [62]. While the zone has been compressed, there is no evidence of any change in zonation on the upper shore, perhaps because the longer high water stand results in greater wetting of the littoral fringe, which compensates for the fall in high water level [49]. The composition of invertebrates within the intertidal area has changed markedly since the 1930s, which may be explained in part by the arrival of immigrant species, which has also affected the communities of other estuaries [49]. Thirty percent of the species found outside the barrage have direct development (without a planktonic larval stage), so it is also possible that their capacity for dispersal within the basin has been reduced [49]. Salinity changes may also be a factor in reduced species penetration [49]. However, the junction between brackish and marine has moved upstream [62] and seasonal variations in salinity have reduced [34], which would imply that upstream conditions in this respect have become more, not less, favourable for marine species.

Thirty fish species continue to breed in the estuary [62], which is also a nursery ground for commercially important species including *Solea solea* (sole), *Dicentrarchus labra* (bass), *Sardina pilchardus* (pilchard), *Sprattus sprattus* (sprat), and *Clupea harengus* (Atlantic herring) [64]. Permanent populations of *Pleuronectes platessa* (plaice) and *Anguilla anguilla* (European eel) are also found within La Rance [64]. It has been reported that fish and cephalopods can pass through the turbines without strike injury, although they emerge disorientated and are more vulnerable to predation [54].

It took a decade after the construction of the barrage for the ecological balance within La Rance to be restored [62]. A regular operating pattern stabilises the abiotic conditions, and any abrupt variations may have significant consequences for biota. In June 1983, the operating mode was changed from ebb-only to two-way, and so previously submerged mudflats were once again exposed. This led to an 80% decline in the abundance of young plaice, which became stranded in the mud and shallow pools during the abrupt transition [62]. Irregular operating periods still occur, including unexpectedly high tides throughout the entire spring period, and also prolonged low water stands, which cause desiccation stress [49]. Fish food chains are heavily dependent on the polychaete worm *Ampharete acutifrons* and *Cerastoderma* cockles, so any unusual operation of the tidal barrage that upsets the delicate balance could have serious implications [64].

5. Mitigation of environmental impacts

5.1. Improvements in conventional barrage design and operation

La Rance barrage is also a useful illustration of how improvements in technology can reduce the environmental impacts of tidal power plants. The construction methods used at La Rance were highly damaging and are no longer employed. La Rance was built *in situ* between two cofferdam walls that completely blocked the estuary, and the only water exchange during the four year construction period was a weekly discharge from the basin [54]. As a result, the marine flora and fauna was virtually eradicated upstream of the barrage, and only species highly tolerant of reduced salinity continued to flourish [62]. Building methods had improved even when construction of the Kislaya tidal barrage began in 1968 (only two years after La Rance was opened). This did not use cofferdam techniques, but instead prefabricated caissons were floated into place to build the barrage walls [34]. Modern construction methods allow the continued exchange of water between up- and down-stream areas during the construction of dams [54].

The materials and architecture of barrage walls can also be designed to allow more natural communities of marine life to become established. For example, natural materials such as coarse woody debris or even shellfish reefs could be incorporated into the construction, while recessing the mortar and leaving out the occasional block (rather than producing smooth walls) provides areas of refuge [19].

Advances in turbine design have occurred in recent years, some of which are aimed specifically at environmental impact mitigations. It is possible for the turbines to be designed in such as way as to reduce the potential for pressure or contact injuries to fish [23] and modern barrages are also likely to include passes so that migrating fish can avoid passage through the turbines in the first place. Methods to prevent fish entering turbines include mesh netting, bubble curtains, flashing lights, and acoustic or electrical signals [23]. Devices including spillways over or under dam gates, fish ladders and fish lifts are also employed to assist fish passage past a barrage [65].

The mode of operation of a tidal barrage can also reduce the environmental impact. As an alternative to ebb- or flood-generation, it is possible to operate a tidal barrage in two-way mode such that electricity is generated on both the ebb and flood tides. The sluice gates remain closed during the early stages of the flood cycle until a sufficient head has built up seaward of the barrage. The gates are then opened, and generation continues until the minimum head is reached, at which point the gates are again closed, this time to trap water within the basin as the tide ebbs. The second (ebb) generating period then begins when the sea level outside the barrage has fallen sufficiently.

Two-way generation utilises a lower head than for ebb-only mode [66], and so has less impact on the tidal regime. Two-way generation does raise the low water level, but to a much lesser extent than under ebb-only generation [4]. Consequently, the area of intertidal habitat that becomes permanently submerged will be reduced. It is difficult to generalise about the magnitude of this reduction because the area of intertidal habitat lost as a result of changes to the tidal regime is very dependent on the bathymetry of the affected estuary. Modelling of five estuaries in northwest and southwest England suggests that between 6% and 30% less intertidal habitat would be lost under two-way operation as compared to ebb-only generation [48]. In addition to reducing habitat loss, two-way generation allows a more natural flushing regime [37], potentially reducing negative effects on water quality. The environmental benefits may not extend throughout the entire estuary, however, as a model has suggested that two-way generation could have more detrimental environmental effects than ebb generation on areas far upstream of a Severn barrage [50].

5.2. Alternative tidal range schemes

Alternative means of utilising tidal range energy are being explored in attempts to reduce possible environmental damage, although these innovations have yet to be tested anywhere in the world. Tidal lagoons would operate in exactly the same way as barrages, and so use proven system components, but the turbines are not contained within a barrier that extends between the banks of the estuary. Instead, perimeter embankments housing the turbines would be constructed to enclose artificial lagoon areas, either against the coastline or entirely offshore [5]. Tidal lagoons are considered to be less environmentally damaging than barrages, as they would not obstruct the entire width of an estuary and also can be sited so as to minimise loss of intertidal areas. However, tidal lagoons would require far greater quantities of construction materials than a barrage, and sourcing these aggregates has environmental and social implications [67].

Tidal reef concepts have also been proposed, which would generate on both the flood and ebb tides but at a very low head of water (about 2 m), greatly reducing the degree to which the incoming or outgoing tide would have to be held back by the barrage [68]. This would allow a more natural tidal regime to be maintained, reducing intertidal habitat loss and water quality impacts. The energy flow through the turbines would also be also lower than for a conventional barrage, potentially reducing impacts on fish passing through the turbines [68]. The tidal reef concept has been taken further in a suggestion for a tidal bar, which proposed designs for a novel low-head turbine with increased efficiency in both directions of flow [69].

The large volume of water moving in and out of hypertidal estuaries creates strong currents, and it has been proposed that these streams, rather than the tidal range *per se*, should be exploited. Tidal fence designs involve arranging tidal current turbines across the width of the estuary. The fence can be an entirely open structure with one or more rows of turbines [70] or the turbines can be incorporated into partial barrages that create a venturi effect, accelerating the speed of the tidal current as the large volume of water flows through the gaps in the dam [71]. Possibly the most novel tidal energy concept is for an alternative tidal fence design, known as the Spectral Marine Energy Converter (SMEC), in which a fence is constructed from a series of vertical and horizontal tubes that utilise the pressure differences created by the passing tidal stream to drive turbines [72].

5.3. *Costs of mitigation*

The cost of mitigation measures that could reduce the environmental impacts of barrages have, to some extent, been estimated. For example, the European Union Habitats Directive requires that developers impacting on protected habitats must pay compensation to ensure the protection of similar ecosystems [73]. Such compensation would add 1–5 p/kWh to the cost of electricity from a Severn Barrage scheme [74].

There are also additional costs associated with technological approaches to impact reduction. Energy from two-way generation is about 10% more expensive than from ebb generation [38], and lagoons have higher constructions costs than traditional barrages as they require longer walls for a given enclosed area [40]. The recent Severn feasibility study considered both barrage and lagoon configurations, and, where equivalent amounts of energy were produced, the lagoon option was predicted to increase build costs by approximately £1 billion, making the unit price of delivered electricity about three times that of the barrage alternative [74]. Lagoons are an untested concept, but the technology employed is mature. There is, therefore, little chance of the costs of lagoons reducing over time, although any actual experience of their operation will provide more accurate cost estimates [5].

Tidal fence schemes employ emerging technology, with the associated high costs. One estimate suggests that a tidal fence in the Severn would produce energy at a price of at least 40 p/kWh, which is more than three times that predicted for a conventional barrage [74]. Fences also produce less energy than barrages for a given length. The energy output of a Severn tidal fence scheme was considered insufficient to meet strategic energy requirements [75].

Higher costs and lower energy outputs are not necessarily a feature of all alternative barrage strategies. Tidal reef designs would use less construction material than conventional barrages, and it has been proposed that a Severn reef scheme could be both cheaper and produce more energy than the corresponding conventional barrage option [68]. As reefs remain a theoretical concept, the economics of such schemes are still uncertain [40,68]. The same is true of the tidal bar: it has been predicted to have a greater energy yield and competitive cost compared to a conventional ebb-only barrage, although it remains unproven [69].

6. Tools to support the decision-making process

The possible employment of mitigation measures highlights two important issues that can influence decisions about tidal barrages. Alternative barrage designs are untested, so there is considerable uncertainty about their efficacy. Also, they come at a higher economic cost: do the ecological benefits justify this additional cost, and how is that decided?

The issue of uncertainty is significant across assessments of potential barrage schemes, not just in terms of potential mitigation measures. The complexity of estuarine ecosystems in general, and the unique nature of individual estuaries, makes it difficult to transfer findings from one situation to another. La Rance provides an example of what has happened to an estuary following the installation and operation of a tidal barrage and, as such, can help to guide decisions on the development of tidal range energy in for UK estuaries. However, experience from La Rance provides only limited opportunities for direct comparisons with specific barrage proposals for the UK. These limitations arise partly because La Rance is a steep-sided ria and therefore not directly comparable to sediment-laden coastal plain estuaries such as the Severn [52]. Also, it is difficult to quantify precisely the levels of impact and recovery at La Rance, as no focused baseline environmental assessment was conducted prior to barrage construction [5]. Other strategies are therefore required when attempting to evaluate the implications of a specific barrage design.

6.1. *Hydrodynamic and ecological modelling*

Modelling the effects of a tidal barrage on estuarine hydrodynamics (e.g. [11]) is a very useful tool for quantifying barrage effects. This could be taken one step further: coupled hydrodynamic and ecological models have been available for some time (e.g. [76]) and such models are available at increasingly high scales of spatial resolution and accuracy due to the advent of unstructured grid modelling in applications such as FVCOM [77]. The challenges of modelling are not trivial, but research by Mateus et al. [78] illustrates that coupled modelling on the scale of an estuary can produce at least qualitative, and in some cases quantitative, results for most of the biogeochemical properties considered, which included nutrients, organic matter, primary producers (phytoplankton) and first level consumers (microzooplankton).

Integrated models have been used to address specific estuarine management issues, particularly related to water quality and eutrophication, which are directly relevant to barrage scenarios. Maar et al. [79], for example, modelled the effects of mixing within the water column and nutrient supply on the growth of mussels. The implications for higher trophic species can also be considered within coupled estuary models. The effect chain approach, which models cause–effect relationships in a series of steps, has been used to investigate how changes in hydrodynamics affect the chain of sediment transport, water quality and algal growth, and the potential implications of this on the availability of habitat for wildfowl [80].

This research suggests that it would be technically feasible to apply coupled modelling to proposed barrage situations, within the limitations of individual models and techniques. Doing so could yield further insights into the likely effects of the hydrodynamic changes caused by a barrage on a range of ecological parameters including primary productivity, benthic organisms and, potentially, species at higher trophic levels including fish

and birds. Integrated modelling approaches have already been applied to other marine renewable energy scenarios, including offshore wind [81].

6.2. Multi-criteria analysis

Determining the magnitude of barrage impacts with an appropriate degree of certainty is only one stage in the evaluation process. A tidal barrage has social and economic as well as environmental effects, and these diverse impacts may be positive or negative, and accrue at different spatial and temporal scales. What is not yet incorporated into standard environmental assessments are tools to effectively quantify the disparate costs and benefits in a way that provides transparency when trade-offs are considered during the decision-making process. Historically, scoping studies and impact assessments for tidal power have made no attempt to evaluate whether the benefit of carbon emission reductions outweighs the costs of loss of habitat, or to assess whether the price premium associated with the options put forward to mitigate barrage impacts is higher, or lower, than the benefit obtained by reducing the environmental damage.

Multi-criteria analysis (MCA) is widely used in assessing trade-offs because it allows large amounts of information to be condensed into a single framework and treated in a consistent manner. At the core of many MCA methods is a process of scoring, ranking or weighting the importance of different costs and benefits, to provide a numerical basis on which to select between different options. MCA includes a range of techniques that address a variety of problems, and it is increasingly being employed by decision-makers within the UK [82].

Within the marine sector, MCA has been employed in a range of situations including for the development of fisheries management plans in which stakeholders and managers identified and scored risks to the delivery of ecological, social and economic objectives [83]. MCA has also been applied to Marine Protected Area management: the Analytic Hierarchy Process has been used to determine the relative importance to stakeholders of four main issues (environmental improvements, social enjoyments and education, local economic benefits, management efficiency), and of subcriteria within each of those main areas [84]. An alternative weighting technique — trade-off analysis — has also been applied to Marine Protected Areas, in which stakeholders weighted their priorities for decision-making criteria and ranked different development scenarios [85].

While MCA has not yet been applied to tidal barrages, it has been used in other ocean renewable energy scenarios. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was used to weight environmental and technical attributes in order to determine the optimal configuration for offshore wind deployment [86]. Weighting of site characteristics though MCA has also been combined with Geographical Information Systems to map areas of optimal resource overlain with information about technical constraints, environmentally sensitive sites, and potential conflicts with other sea uses [87].

6.3. Economic valuation

An alternative approach to MCA would be to quantify each social and environment change using a common metric, and conduct a cost-benefit analysis. Economic valuation of natural resources and ecosystem services aims to provide this common metric. It allows for those values of ecosystems for which there are no markets (and so no defined prices) to be quantified in terms that permit their direct comparison with marketed goods and services [88,89]. The growing acceptance of ecosystem valuation and its important role in informing management strategies was highlighted by the Millennium Ecosystem Assessment [90], and, more recently in The Economics of Ecosystems and Biodiversity (TEEB) [91], and the UK National Ecosystem Assessment [92].

Within the marine environment, there are some sectors for which market prices exist, including fish, seafood and raw materials such as aggregates. Monetary value can be assigned to other marine sectors through a variety of techniques, including valuing the damage avoided as a result of the ocean's provision of climate regulation (avoidance cost); determining the cost of manmade alternatives to natural systems such as nutrient cycling (replacement cost) and eliciting the willingness to pay amongst member of the public for the continued existence of species and habitats (stated preference) [93].

An attempt was made during the most recent Severn feasibility study to monetise the habitat loss resulting from different barrage designs, which showed a net environmental cost for each of the five schemes, ranging from £5.9 million to £218.6 million under different scenarios and assumptions [94]. The need to interpret the results with caution, due to high levels of uncertainty, was explicitly emphasised in the report, as was the need for more context-specific primary data: in the absence of empirical data, the work was based on the transfer of values from a global wetland meta-analysis.

7. Conclusions

The use of marine energy is intended to mitigate climate change, and thus provide a global environmental benefit, but its deployment is not without local environmental costs. Available evidence suggests that the ecological impacts of a tidal barrage would be significant, particularly the loss of intertidal habitat and the associated impacts on waders and wildfowl; the likely build-up of contaminants and increased risk of eutrophication; the obstruction to the passage of migratory fish; and the changes in the benthic communities due to the altered sedimentation regime. However, it is likely that there would also be benefits to marine species, including an increase in local biodiversity due to the availability of a hard substrate for colonisation, and increased primary productivity (due to reduced turbidity), potentially providing some compensation for loss of habitat. The development of La Rance barrage caused significant mortality of marine species, primarily due to the construction methods and subsequent abrupt changes in the barrage operating regime, but this case study also demonstrates that the ecosystem can recover over time, to the point where the estuary has been designated as a protected area in recognition of the species present, including the birdlife.

The social and economic implications of barrage construction must also be considered. Potential benefits include road and rail links across the barrage; increased employment; improved upstream conditions for recreation; and flood defences. The possible costs, however, include an increase in local flood risk due to erosion and restriction of outfalls; restrictions on navigation by commercial and recreational vessels; and a reduction in wellbeing where people are affected by noise or changes to the seascape.

The existing evidence does not provide a clear case for or against tidal barrages, and so better tools for decision-making are required. These should include modelling of both hydrodynamic and ecological implications to improve understanding of likely impacts at a given site, and also the use of multicriteria analysis and ecosystem valuation as frameworks within which trade-offs can be assessed transparently. Ecosystem valuation is also essential in cost-benefit analysis of mitigation measures that aim to reduce the environmental impact of tidal barrages.

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References

[1] HM Government. The UK low carbon transition plan: national strategy for climate and energy; 2009.
[2] HM Government. The carbon plan: delivering our low carbon future; December 2011.
[3] Regen SW. The road to 2020: an analysis of renewable energy options in the South West of England. Report prepared by Regen SW and the South West Regional Development Agency; 2008.
[4] Burrows R, Walkington IA, Yates NC, Hedges TS, Wolf J. The tidal range energy potential of the West Coast of the United Kingdom. Applied Ocean Research 2009;31(4):229–38.
[5] Sustainable Development Commission. Turning the tide; 2007.
[6] Langston WJ, Jonas PJC, Millward G. The Severn Estuary and Bristol Channel: a 25 year critical review. Marine Pollution Bulletin 2010;61(1–3):1–4.
[7] DECC. Severn tidal power feasibility study: conclusions and summary report. Department of Energy and Climate Change; October 2010: 75pp.
[8] BBC. 〈http://www.bbc.co.uk/news/uk-wales-south-east-wales-19311254〉; 19 August 2012 [accessed 03.09.12].
[9] Northwest Regional Development Agency. Tidal energy in England's Northwest. One of Europe's top tidal energy opportunities; 2009.
[10] Baker C. Tidal power. Energy Policy 1991;19(8):792–7.
[11] Burrows R, Walkington I, Yates N, Hedges T, Chen D, Li M, et al. Tapping the tidal power potential of the eastern irish sea. Final report of the Joule project JIRP106/03; 2009.
[12] JNCC. UK protected sites. 〈http://www.jncc.gov.uk/page-4〉 [accessed 27.04.10].
[13] Gill AB. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. Journal of Applied Ecology 2005;42:605–15.
[14] Bock MJ, Miller DC. Seston variability and daily growth in Mercenaria mercenaria on an intertidal sandflat. Marine Ecology Progress Series 1994;114:117–27.
[15] Harvey M, Gauthier D, Munro J. Temporal changes in the composition and abundance of the macro-benthic invertebrate communities at dredged material disposal sites in the Anse à Beaufils, Baie des Chaleurs, Eastern Canada. Marine Pollution Bulletin 1998;36(1):41–55.
[16] Miller DC, Muir CL, Hauser OA. Detrimental effects of sedimentation on marine benthos: what can be learned from natural processes and rates? Ecological Engineering 2002;19:211–32.
[17] Trannum HC, Nilsson HC, Schaanning MT, Øxnevad S. Effects of sedimentation from water-based drill cuttings and natural sediment on benthic macrofaunal community structure and ecosystem processes. Journal of Experimental Marine Biology and Ecology 2010;383(2):111–21.
[18] Holdway DA. The acute and chronic effects of wastes associated with offshore oil and gas production on temperate and tropical marine ecological processes. Marine Pollution Bulletin 2002;44:185–203.
[19] Bulleri F, Chapman MG. The introduction of coastal infrastructure as a driver of change in marine environments. Journal of Applied Ecology 2009;47(1):26–35.
[20] Moschella PS, Abbiati M, Åberg P, Airoldi L, Anderson JM, Bacchiocchi F, et al. Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design. Coastal Engineering 2005;52:1053–71.
[21] Larinier M. Environmental issues, dams and fish migration. FAO Fisheries Technical Paper 2001;419:p. 45–89.
[22] Henderson PA, Bird DJ. Fish and macro-crustacean communities and their dynamics in the Severn Estuary. Marine Pollution Bulletin 2010;61(1–3):100–14.
[23] Turnpenny AWH, Clough S, Hanson KP, Ramsay R, McEwan D. Risk assessment for fish passage through small, low-head turbines. ETSU H/06/00054/REP. Report prepared for the Department of Trade and Industry; 2000.
[24] Madsen PT, Wahlberg M, Tougaard J, Lucke K, Tyack P. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Marine Ecology Progress Series 2006;309:279–95.
[25] Nedwell J, Langworthy J, Howell D. Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise. Report no. 544 R 0424. Research commissioned by the Collaborative for Offshore Wind Research Into the Environment (COWRIE); May 2003.
[26] Parsons Brinckerhoff. Severn tidal power — scoping topic paper. Noise. Report prepared for the Department for Energy and Climate Change; 2008.
[27] Wade L, Whitehead H, Weilgart L. Conflict of interest in research on anthropogenic noise and marine mammals: does funding bias conclusions? Marine Policy 2010;34(2):320–7.
[28] Robert Gordon University. A scoping study for an environmental impact field programme in tidal current energy. ETSU T/04/00213/REP. Report prepared for the Department of Trade and Industry. DTI Pub/URN 02/882; 2002.
[29] Kikuchi R. Risk formulation for the sonic effects of offshore wind farms on fish in the EU region. Marine Pollution Bulletin 2010;60:172–7.
[30] Parsons Brinckerhoff. Severn tidal power — scoping topic paper. Marine ecology. Report prepared for the Department for Energy and Climate Change; 2008.
[31] Montgomery JC, Jeffs A, Simpson SD, Meekan M, Tindal C. Sound as an orientation cue for the pelagic larvae of reef fishes and decapod crustaceans. Advances in Marine Biology 2006;51:143–96.
[32] Kingsford MJ, Leis JM, Shanks A, Lindeman KC, Morgan SG, Pineda J. Sensory environments, larval abilities and local self-recruitment. Bulletin of Marine Science 2002;70(1):309–40.
[33] Koschinski S, Culik BM, Henriksen OD, Tregenza N, Ellis G, Jansen C, et al. Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. Marine Ecology Progress Series 2003;265:263–73.
[34] Frau JP. Tidal energy: promising projects — La Rance — a successful industrial scale experiment. IEEE Transactions on Energy Conversion 1993;8(3):552–8.
[35] ABP Mer and HR Wallingford. Severn tidal power — scoping topic paper. Hydraulics and geomorphology. Report prepared for the Department for Energy and Climate Change; 2008.
[36] Burton NKH, Musgrove AJ, Rehfisch MM, Clark NA. Birds of the Severn Estuary and Bristol Channel: their current status and key environmental issues. Marine Pollution Bulletin 2010;61(1–3):115–23.
[37] Prandle D. Design of tidal power schemes. Maritime Engineering 2009;162:147–53.
[38] Black and Veatch. Tidal Power in the UK. Research Report 3 — review of severn barrage proposals. Report prepared for the Sustainable Development Commission; 2007.
[39] Parsons Brinckerhoff. Severn Tidal Power — scoping topic paper. Ornithology. Report prepared for the Department for Energy and Climate Change; 2008.
[40] Halcrow Group Ltd. Mott MacDonald and R.S.K. Group plc. Solway energy gateway. Feasibility study; December 2009.
[41] Scott Wilson, EDF. Mersey tidal power. Feasibility study: stage 1. Options report; February 2010.
[42] Goss-Custard JD, Burton NKH, Clark NA, Ferns PN, McGrorty S, Reading CJ, et al. Test of a behaviour-based model: response of shorebird mortality to habitat loss. Ecological Applications 2006;16(6):2215–22.
[43] Norris K, Brindley E, Cook T, Babbs S, Forster Brown C, Yaxley R. Is the density of redshank Tringa tetanus nesting on saltmarshes in Great Britain declining due to changes in grazing management? Journal of Applied Ecology 1998;35:621–34.
[44] Burton NHK, Rehfisch MM, Clark NA. Impacts of sudden winter habitat loss on the body condition and survival of redshank Tringa tetanus. Journal of Applied Ecology 2006;43:464–73.
[45] Goss-Custard JD, Stillman RA, West AD, Caldow RWG, McGrorty S. Carrying capacity in overwintering migratory birds. Biological Conservation 2005;105:27–41.
[46] Underwood GJC. Microphytobenthos and phytoplankton in the Severn Estuary, UK: present situation and possible consequences of a tidal energy barrage. Marine Pollution Bulletin 2010;61(1–3):83–91.
[47] Warwick RM, Somerfield PJ. The structure and function of the benthic macrofauna of the Bristol Channel and Severn Estuary, with predicted effects of a tidal barrage. Marine Pollution Bulletin 2010;61(1–3):92–9.
[48] Wolf J, Walkington IA, Holt J, Burrows R. Environmental impacts of tidal power schemes. Maritime Engineering 2009;162:165–77.
[49] Little C, Mettam C. Rocky shore zonation in the Rance tidal power basin. Biological Journal of the Linnean Society 1994;51:169–82.
[50] Xia J, Falconer RA, Lin B. Impact of different operating modes for a Severn Barrage on the tidal power and flood inundation in the Severn Estuary, UK. Applied Energy 2010;87(7):2374–91.
[51] Kirby R. Distribution, transport and exchanges of fine sediment, with tidal power implications: severn Estuary, UK. Marine Pollution Bulletin 2010;61(1–3):21–36.
[52] Pethick JS, Morris RKA, Evans DH. Nature conservation implications of a Severn tidal barrage — a preliminary assessment of geomorphological change. Journal for Nature Conservation 2009;17:183–98.
[53] Parsons Brinckerhoff. Severn tidal power — scoping topic paper. Marine and estuarine water quality. Report prepared for the Department for Energy and Climate Change; 2008.
[54] Kirby R, Reitière C. Comparing environmental effects of Rance and Severn barrages. Maritime Engineering 2009;162:11–26.
[55] Langston WJ, Pope ND, Jonas PJC, Nikitic C, Field MDR, Dowell B, et al. Contaminants in fine sediments and their consequences for biota of the Severn Estuary. Marine Pollution Bulletin 2010;61(1–3):68–82.

[56] Parsons Brinckerhoff. Severn tidal power — scoping topic paper. Other sea uses. Report prepared for the Department for Energy and Climate Change; 2008.
[57] Faber Maunsell, Metoc. Scottish marine renewables strategic environmental assessment (SEA) non-technical summary. Report prepared for the Scottish Executive by: Faber Maunsell and Metoc Plc; March 2007.
[58] Parsons Brinckerhoff. Severn tidal power — scoping topic paper. Landscape and seascape. Report prepared for the Department for Energy and Climate Change; 2008.
[59] Parsons Brinckerhoff. Severn tidal power — scoping topic paper. Historic environment. Report prepared for the Department for Energy and Climate Change; 2008.
[60] AECOM, Metoc. Strategic environmental assessment (SEA) of offshore wind and marine renewable energy in Northern Ireland environmental peport, vol. 1: main report. Department of Enterprise, Trade and Investment (DETI); December 2009.
[61] Environment Agency. Scoping guidelines on the environmental impact assessment (EIA) of projects. I6: tidal power developments; 2002.
[62] Retière C. Tidal power and the aquatic environment of La Rance. Biological Journal of the Linnean Society 1994;51:25–36.
[63] MAIA. Estuaire de la Rance — Site d'importance communautaire. 〈http://www.maia-network.org/homepage/marine_protected_areas/mpa_data_sheets/an_mpa_datasheet?gid=336〉 [accessed 24.08.12].
[64] Le Mao P. Feeding relationships between the benthic infauna and the dominant benthic fish of the Rance estuary (France). Journal of the Marine Biological Association of the United Kingdom 1986;66:391–401.
[65] Schilt CR. Developing fish passage and protection at hydropower dams. Applied Animal Behaviour Science 2007;104:295–325.
[66] Ferreira RM, Estefen SF. Alternative concept for a tidal power plant with reservoir restrictions. Renewable Energy 2009;34:1151–7.
[67] Crumpton NA. Severn barrage or tidal lagoons? A comparison. Friends of the earth briefing; January 2004.
[68] Atkins Ltd. Severn Barrage. Feasibility of tidal reef scheme 5079276/RPT/01 Rev 1; 2008.
[69] Rolls Royce, Atkins. Severn Embryonic technologies scheme concept design of a very-low head dual generation tidal scheme for the Severn Estuary, vol. 1: summary report; 2010.
[70] Severn Tidal Fence Consortium. Severn embryonic Technologies scheme. Final report. Report V3.1. 08.01.2010. ITP/UKP01087; 2010.
[71] Peel and North West Regional Development Agency. Mersey tidal power feasibility study. Stage 1 options report. Non-technical summary; February 2010.
[72] Department of Energy and Climate Change. Severn embryonic technologies scheme. 〈http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/severn_tidal_power/embryonic_tech/embryonic_tech.aspx〉 [accessed 2010].
[73] Treweek J. Scoping study for the design and use of biodiversity offsets in an english context. Final Report to DEFRA (Contract NE 0801); April 2009.
[74] Parsons Brinckerhoff. Analysis of options for tidal power development in the Severn Estuary — interim options analysis report, vol. 1. Report prepared for the Department for Energy and Climate Change; 2008.
[75] Department of Energy and Climate Change. Severn tidal power feasibility study: conclusions and summary report; October 2010.
[76] Allen JI. A modelling study of ecosystem dynamics and nutrient cycling in the Humber plume, UK. Journal of Sea Research 1997;38:333–59.
[77] Kim T, Khangaonkar T. An offline unstructured biogeochemical model (UBM) for complex estuarine and coastal environments. Environmental Modelling and Software 2012;31:47–63.
[78] Mateus M, Vaz N, Neves R. A process-oriented model of pelagic biogeochemistry for marine systems. Part II: application to a mesotidal estuary. Journal of Marine Systems 2012;94:S90–101.
[79] Maar M, Timmermann K, Petersen JK, Gustafsson KE, Storm LM. A model study of the regulation of blue mussels by nutrient loadings and water column stability in a shallow estuary, the Limfjorden. Journal of Sea Research 2010;64:322–33.
[80] Spiteri C, van Maren B, van Kessel T, Dijkstra J. Effect chain modelling to support ems-dollard management. Journal of Coastal Research 2011; SI61:226–33.
[81] Maar M, Bolding K, Petersen JK, Hansen JLS, Timmermann K. Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm. Denmark Journal of Sea Research 2009;62:159–74.
[82] Department for Communities and Local Government. Multi-criteria analysis: a manual; January 2009.
[83] Fletcher WJ, Shaw J, Metcalf SJ, Gaughan DJ. An ecosystem based fisheries management framework: the efficient, regional-level planning tool for management agencies. Marine Policy 2010;34:1226–38.
[84] Heck N, Dearden P, McDonald A. Stakeholders' expectations towards a proposed marine protected area: a multi-criteria analysis of MPA performance criteria. Ocean and Coastal Management 2011;54:687–95.
[85] Brown K, Adger WN, Tompkins E, Bacon P, Shim D, Young K. Trade-off analysis for marine protected area management. Ecological Economics 2001;37: 417–34.
[86] Lozano-Minguez E, Kolios AJ, Brennan FP. Multi-criteria assessment of offshore wind turbine support structures. Renewable Energy 2011;36(11): 2831–7.
[87] Nobre A, Pacheco M, Jorge R, Lopes MFP, Gato LMC. Geo-spatial multi-criteria analysis for wave energy conversion system deployment. Renewable Energy 2009;34:97–111.
[88] Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, et al. The value of the world's ecosystem services and natural capital. Nature 1997;387:253–60.
[89] Barbier EB. Valuing ecosystem services as productive inputs. Economic Policy 2007;22(49):177–229.
[90] Millennium Ecosystem Assessment. Ecosystems and human well-being: biodiversity synthesis. Washington, DC: World Resources Institute; 2005.
[91] The Economics of Ecosystems and Biodiversity (TEEB): Ecological and Economic Foundations. Kumar Pushpam, editor. London: Earthscan; 2010.
[92] UK National Ecosystem Assessment Technical Report. Cambridge: UNEP-WCMC; 2011.
[93] Beaumont NJ, Austen MC, Mangi SC, Townsend M. Economic valuation for the conservation of marine biodiversity. Marine Pollution Bulletin 2008;56:386–96.
[94] Hime S, Ozdemiroglu E. Economic valuation of the effect of the shortlisted tidal options on the ecosystem services of the Severn Estuary. Final Technical Report prepared for the Department of Energy and Climate Change by Economics for the Environment Consultancy (eftec), London; 2010.